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Large size biogas-fed Solid Oxide Fuel Cell power plants with carbon dioxide management: Technical and economic optimization

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HIGHLIGHTS

- Five large SOFC power plant configurations are evaluated.
- SOFC is fuelled by digester gas from a wastewater treatment plant.
- Fuel Utilization is the design variable that most influences the efficiency.
- Gas turbine integration improves efficiency with optimal stack pressure at 4–5 bar.
- Carbon capture entails a penalty of more 10% in pressurized configurations.

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ABSTRACT

This article investigates the techno-economic performance of large integrated biogas Solid Oxide Fuel Cell (SOFC) power plants. Both atmospheric and pressurized operation is analysed with CO_2 vented or captured. The SOFC module produces a constant electrical power of 1 MWe.

Sensitivity analysis and multi-objective optimization are the mathematical tools used to investigate the effects of Fuel Utilization (*FU*), SOFC operating temperature and pressure on the plant energy and economic performances. *FU* is the design variable that most affects the plant performance. Pressurized SOFC with hybridization with a gas turbine provides a notable boost in electrical efficiency. For most of the proposed plant configurations, the electrical efficiency ranges in the interval 50–62% (LHV biogas) when a trade-off of between energy and economic performances is applied based on Pareto charts obtained from multi-objective plant optimization. The hybrid SOFC is potentially able to reach an efficiency above 70% when *FU* is 90%. Carbon capture entails a penalty of more 10 percentage points in pressurized configurations mainly due to the extra energy burdens of captured CO_2 pressurization and oxygen production and for the separate and different handling of the anode and cathode exhausts and power recovery from them.

1. Introduction

The production of both thermal and high efficiency electrical power with SOFC systems represents an interesting alternative to conventional power and thermal plants. However, at the current state of the art, the main market application for SOFC systems seems to be represented by the residential energy sector [1] with also some installations at the larger scale with Bloom Energy [2]. The research recognizes the high potential of this technology in the power generation. Still, there are issues that need to be solved before SOFC can become really competitive in the global energy market. In fact, especially in the last years, some demonstration projects have been conducted, mainly in stationary power generation (also in Combined Heat and Power mode, CHP), which have revealed that SOFC power plants cannot be introduced in the market until the problems related to lifetime extension and cost reduction are solved [3]. However, a significant progress has been achieved concerning the electrical efficiency and the value now representing the state of the art is higher than 60% [4]. SOFC power plants are still on the development phase and their high performances have been demonstrated for stack sizes <100 kW, which could be used in small CHP units (suitable for the residential

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Symbols and abbreviations

A_{tot} [m^2]	Totale active surface
A_{stack} [m^2]	Total surface of the stack
AC [€]	Annual cost
AP [€]	Annual profit
ASR [Ω cm^2]	Area Specific Resistance
BEC [€]	Bare Erected Cost
CF [€]	Cash Flow
CHP [−]	Combined Heat and Power
d_{ASR} [%]	Degradation rate
d_f [%]	Discounting factor
dep [€]	Depreciation
FU [%]	Fuel Utilization
I [A]	Current
IR [%]	Internal reforming rate
i_R [%]	Interest rate
j [A cm^{-2}]	Current density
LHV [MJ m^{-3}]	Lower Heating Value
LMTD [°C]	Logarithmic mean temperature difference
$N_{HE,min}$ [−]	Minimum number of heat exchangers
NPV [M€]	Net present value
OCV [V]	Open Circuit Voltage
O&M [€]	Operations & Maintenance
p [bar]	Pressure
$\dot{Q}$	[kW] Thermal power
R(*y*) [€]	Revenues
r_{loss} [%]	Heat loss rate
SC [%]	Steam to Carbon ratio
sc [−]	Scaling factor
T [°C]	Temperature
t [s]	Time
TOC [€]	Total overnight cost
TPC [€]	Total plant cost
V [V]	Voltage
$\dot{V}$	[m^3 s^{-1}] Volumetric flow
W	[kW] Mechanical power
$W_{el,DC}$ [kW]	Power of the SOFC in DC
W_{EL} [kW]	Electrical power
WACC [%]	Weighted average cost of the capital
y [y]	Year
η_{el}	[%] Electrical efficiency
η_{gen}	[%] Electrical generator efficiency
η_{inv}	[%] Inverter efficiency
η_{is}	[%] Isentropic efficiency

sector); however it is supposed that these systems could also be efficiently adopted for larger power productions [5].

The high performances achievable are especially due, in the future perspectives, to the possibility of having hybrid plants where SOFCs are coupled with small gas turbines (<500 kW). In fact, the fuel cell stack can in principle operate at atmospheric pressure or it can be pressurized, so that it is possible to achieve better performances. The predicted efficiencies are around to 65% (70% could also be achieved) and the delivered power ranges from 100 kW to 20–30 MW ([6, 7]).

SOFCs foresee a better competitiveness not just from a point of view orientated to the energy productivity, but also to the environmental safeguard. The emission levels of NO_x and SO_x are very low, especially for the technology that allows an easier and cheaper integration with CCS (Carbon Capture and Storage). CCS is nowadays developed in a large-scale view, but, when it will be applied also to decentralized power generators (as probably required by the future energy market), then the integrated SOFC power plants could have the potential to represent an important technology [8].

Another good point for SOFCs is the fuel flexibility: pure hydrogen, biogas, methanol, or other liquid mixtures rich of methane can be used. Waste-derived biogas produced in water treatment plants represents an attractive renewable source of energy from both an economic and environmental point of view [9]. From the point of view of CO_2 management, this fuel contains “renewable” carbon (from biomass source), and therefore the CO_2 removal from the exhausts would determine a “negative” CO_2 emission situation, allowing a CO_2-emission stock exchange with plants fed by fossil fuels.

This plant configuration has been already tested at a proof-of-concept level in the SOFCOM project [10]. SOFCOM is an EU funded research project that aims to study the technical and economic feasibility of CHP systems based on SOFC fuelled by locally produced biogenous fuels. The demonstration plant in Torino [10] adopts, as reference fuel, biogas produced locally in a WWTU (Waste-Water Treatment Unit): this type of biogas represents a by-product of the unavoidable process that is required to reduce the biological activity of pre-treated sludge and for this reason it is assumed that it is available for free for the SOFC.

In this context, the paper considers different configurations of integrated SOFC power plants of large size, all fuelled by biogas produced in a WTTU. For each design a technical and economic analysis is implemented. Also, three main plant variables:

- Fuel utilization (*FU*)
- Stack temperature (T_{SOFC})
- Stack pressure (p_{SOFC})

A sensitivity analysis is performed in respect to these variables in order to understand the dependency of the integrated plant performance toward these parameters. Furthermore, a multi-objective optimization (MOO) is implemented to identify the best operating conditions from either an energy or economic stand point of view.

As will be discussed in the methodology chapter, one of the main tool used in this work is OSMOSE [11], a Matlab based package developed by EPFL [12] that allows to create an interface between Matlab itself and a process modelling software (e.g., Aspen Plus® or Vali®). In this work, OSMOSE is employed to perform thermal integration of hot/cold streams via pinch analysis methodology, sensitivity analysis and MOO optimizations. The effectiveness of this tool has been proved in other scientific reports where complex energy systems were studied and optimized. For example, the software [13] has been used to optimize the design conditions of a sugar-cane process integrated to a CHP system fuelled by bagasse (main by-product from juice extraction) or, in Ref. [14], it allowed the optimization of different SOFC systems from a thermo-economic point of view.

2. Methodology

2.1. Approach adopted

Each plant configuration has been modelled with Aspen Plus®. Its library does not include fuel cells. For this reason, it was necessary to integrate the electrochemical model of the SOFCs: the